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B. J. TEEGARDEN
F. B. McDONALD
J. H. TRAINOR
E. C. ROELOF
W. R. WEBBER

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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B. J. TEEGARDEN, F. B. McDONALD AND J. H. TRAINOR
Goddard Space Flight Center, Greenbelt, Maryland

E. C. ROELOF AND W. R. WEBBER
University of New Hampshire, Durham, N. H.

ABSTRACT

The Goddard-University of New Hampshire cosmic-ray experiment on Pioneer has provided measurements of the differential radial gradient of cosmic-ray helium nuclei between 1 and 3 AU. Upper limits are quoted between 10 and 500 MeV/nuc which are everywhere <25%/AU and in some cases substantially smaller. The integral proton gradient (>56 MeV) was also measured and found to have the following values: 2.4 ± 0.3%/AU (1-2 AU), 7.6 ± 0.7%/AU (2-3 AU).

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PIONEER 10 MEASUREMENTS OF THE DIFFERENTIAL AND INTEGRAL COSMIC-RAY GRADIENT BETWEEN 1 AND 3 AU

I. INTRODUCTION

We report in this letter the first complete measurements of the differential gradient of cosmic-ray helium nuclei in the energy range 10-500 MeV/nuc between 1 and 3 AU. These measurements span the energy and spatial regions where modulation effects were thought to be most important and where gradients were expected to be largest.

A knowledge of the low energy component is vital to understanding the total-energy content, acceleration and interstellar travel of galactic cosmic rays. However, despite many extensive investigations carried out at 1 AU, it has not proven possible to remove the effects of solar modulation and determine the interstellar spectra. A measurement of the differential gradient over a large radial distance is the only feasible method of studying low-energy galactic cosmic rays. Furthermore, the radial dependence of the gradient is important in understanding energetic particle transport in the solar system as well as the dimension of the effective modulation region.

Our results are derived from the Goddard - University of New Hampshire cosmic-ray experiment on board the Pioneer 10 spacecraft. The experiment consists of a coordinated set of three solid-state telescopes. These instruments are capable of providing high-resolution, low-background measurements of charge, mass, and energy spectra in the ranges $1 \leq Z \leq 16$ and $3 \leq E \leq 500$ MeV/nuc.

II. DIFFERENTIAL He SPECTRA AND GRADIENT

The differential helium spectral measurements from the Goddard - University of New Hampshire experiment on Pioneer 10 are shown in Fig. 1. The data cover the range 10-500 MeV/nuc. Three time periods are shown corresponding to mean values of the heliocentric radial distance of 1.04, 1.91, and 2.80 AU, respectively. It is immediately and strikingly obvious that, within experimental errors, the three spectra are identical. These spectra are in quite good agreement with the helium spectra reported by Garcia-Munoz *et al*. (1973) and by van Hollebeke and McDonald (1973) during similar time periods. The Pioneer spectra show the same curious flat region between 10 and ~80 MeV/nuc as reported by the other observers. Care has been taken to eliminate any possible contamination of the data by energetic solar particles.

The Goddard cosmic-ray telescope on IMP VI was used as a reference detector fixed at 1 AU. Spectra were derived from IMP VI during the same time periods as the Pioneer spectra shown in Fig. 1. These spectra were also identical within errors, i.e. during the time period covered by the Pioneer data there was no observable time variation in the helium intensity at 1 AU.

It should also be pointed out that the period during which these measurements were taken is rather unique. The low-energy (~50 MeV/nuc) helium intensity has returned to nearly its value at the last solar minimum (1965). The 60-MeV proton intensity, however, lags significantly behind and has not reached its 1965 level. In addition, the low-energy helium intensity remained reasonably constant during 1972, while the proton intensity exhibited a significant variability (van Hollebeke and McDonald 1973). A similar phenomena was noted over the last solar maximum (see for example, Lockwood et al. 1972, van Hollebeke et al. 1972) where there was a significant phase lag or "hysteresis effect" between changes in the low rigidity cosmic rays and the high rigidity component. In 1972 the low energy components were in the process of closing this hysteresis loop.

The radial gradients derived from the helium spectra of Fig. 1 are shown in Figs. 2a and b. The data have been divided into two periods corresponding to the radial-distance intervals 1.02-1.97 AU. and 1.97-2.90 AU., respectively. All data points shown are within ~ 2 standard deviations of zero. A statistically accurate reference at 1 AU for the 10-20 MeV/nuc interval was not available to us at the time of writing. To derive a gradient for the 10-20 MeV/nuc interval we have assumed that the time variations can be neglected. In view of the absence of time variations at higher energies, the uncertainty in this point due to time variations is probably smaller than the already quite large statistical uncertainty. The two sets of data taken as a whole indicate that the helium gradients are everywhere in the 30-500 MeV/nuc interval less than 25%/AU and, in fact, are probably much smaller. In Fig. 2a the differential helium gradient measurements of other observers are also shown. The point of McKibben et al. (1973) is from the University of Chicago cosmic-ray experiment on Pioneer 10. We therefore have two independent helium gradient measurements on the same spacecraft which are in agreement within errors. The Pioneer 8 and 9 measurements of Webber and Lezniak (1973) show a significant positive departure from zero in the vicinity of 100 MeV/nuc. A similar peak at higher energies (~400 MeV) also occurred in their differential proton gradient. It is important to note that the Webber and Lezniak gradient measurements were made during 1968-69, a time period where the cosmic-ray intensity was experiencing nearly its maximum modulation during the solar cycle and where larger gradients could be expected to occur. The Mariner IV measurements of O'Gallagher and Simpson (1967), however, were taken during 1964-65, a period near minimum solar activity where the fluxes at 1 AU were nearly the same as during 1972. The differences between our measurements and theirs are then not easily explainable in terms of solar cycle variations.

Theoretical calculations of the differential helium gradient performed by Urch and Gleeson (1972) are also shown in Fig. 2a. These authors have used cosmic-ray electron data to derive the modulation and gradient of protons and helium nuclei. The electrons are particularly useful in that their interstellar spectrum can be inferred from radio observations. By a comparison of the interstellar and 1 AU electron spectra they determined the total electron modulation, which, in turn, provided a value for the parameter $\Phi = \int_1^R V/3K_1(r)\,dr$ where $K_1(r)$ is the radially-dependent part of the diffusion coefficient, V is the solar-wind velocity, and R is the distance to boundary (in AU) of the modulation region. A knowledge of this quantity, combined with the local value of the diffusion coefficient (as a function of rigidity), determined from the magnetic-field power spectrum, is sufficient for the determination of the differential gradient at 1 AU. Three different curves are shown in Fig. 2a corresponding to three values for the diffusion coefficient. These values are intended to cover the range of diffusion coefficients given by Jokipii and Coleman (1968) for a period near solar minimum (1964-65). The curve corresponding to the largest diffusion coefficient, $\kappa(1\ \mathrm{GV}) = 2.8 \times 10^{21}\mathrm{cm}^2/\mathrm{sec}$, is in reasonable agreement with the data.

Greater statistical accuracy can be achieved by using the integral rate of all particles that penetrate the high-energy telescope (nuclei > 56 meV/nuc and electrons > 7 meV). Since this rate is determined by a three-fold coincidence, it is almost totally insensitive to gamma-ray background from the radio-isotope power supplies. It is also relatively insensitive to instrument drifts and the long-term stability has been verified by in-flight checks.

In Fig. 3a, we show the daily-average Pioneer 10 counting rate > 56 MeV/nuc as a function of time and heliocentric distance. Also shown is a similarly-formed counting rate (> 80 MeV/nuc) from the Goddard cosmic-ray experiment on IMP-VI. The difference in energy thresholds can be neglected since the integral intensity changes by < 1% between 56 and 80 MeV. Shaded areas indicate time periods where either a significant amount of solar activity or a Forbush decrease was present.

The ratio of the Pioneer 10 and IMP VI counting rates is shown in

Fig. 3b. As with Fig. 3a, it has been normalized to 100 at 1 AU to show the percentage variations. The data have been divided into two periods corresponding roughly to the radial intervals 1-2 and 2-3 AU respectively. Least-squares linear fits have been performed on each of these sets of data. The gradient is simply the slope of the best-fit line divided by the mean value of the ratio during the interval. The best-fit lines and their slopes are indicated in Fig. 3b. Between $\sim$ 1 and 2 AU a gradient of 2.4 $\pm$ 0.3%/AU is obtained. The error quoted is just the standard error in the slope assuming that the fluctuations are random and uncorrelated. These fluctuations are a combination of statistical variations (see typical error bar in Fig. 3b) and short-term modulation effects caused by fluctuations in the interplanetary magnetic field. The quoted error in the gradient should be viewed with this in mind, and the actual uncertainty may, in fact, be somewhat larger.

Between 2 and 3 AU we observe a significant increase in the gradient. We obtain a value of 7.6 $\pm$ 0.7%/AU, approximately a factor of three larger than the value between 1 and 2 AU. The large gap in the data is associated with the intense solar activity in July and August, 1972. A huge Forbush decrease occurred in association with the large flares in early August. A long, slow recovery period ensued lasting at least 30 days. The crucial question is, therefore, whether the increased gradient that we observe represents a residual effect of disturbed interplanetary conditions resulting from the intense solar activity in August, or is truly representative of quiet-time equilibrium conditions in interplanetary space. The increased gradient persists for at least 100 days after the Forbush decrease. To be sure that this is an equilibrium effect, however, we will have to await the arrival of more data.

In Table 1 we compare our integral gradient measurements with those of two other experiments on Pioneer 10. All experiments agree that the gradients are small. In detail, however, there are some differences. The University of Iowa (Van Allen 1973) result is smaller than either the University of Chicago (McKibben _et al_. 1973) or the Goddard-University of New Hampshire results between 1 and 2 AU. It should be pointed out that the University of Iowa detector differs from the other two in that it is omni-directional. The Goddard-University of New Hampshire and University of Chicago instruments are similar in that they rely on multiple coincidences to define the acceptance cones and energy thresholds of the detectors. Neither the University of Iowa or University of Chicago experiments report an increase in the gradient between 2 and 3 AU.

III. DISCUSSION

We have reported the first measurements of the differential helium gradient in the 10-500 MeV/nuc interval at large distances from the earth's orbit. The small values we obtain are generally consistent with zero within errors. Due to large uncertainties in the local value of the diffusion coefficient there does not at present appear to be any difficulty reconciling theory and experiment.

With regard to the integral gradient, all Pioneer-10 experiments agree that it is small. Differences in detail, however, are probably present. Recent theoretical studies by Fisk (1973) have predicted an average integral proton gradient between 1 and 4 AU of 3%/AU. Furthermore, he predicted a gradient increasing with heliocentric radial distance. This behavior results from the assumption of a radial dependence for the diffusion coefficient, $\kappa \propto r$. Such a dependence for κ appears to be consistent with the recently-reported Pioneer-10 magnetic-field measurements (Smith et al. 1973). It is also important that within Fisk's model no significant modulation occurred beyond 10 AU. One can therefore conclude that the small gradients inside 4 AU do not necessarily imply a very large modulation region. There is therefore a reasonable hope that during its lifetime Pioneer 10 may make measurements of a relatively undistorted interstellar spectrum.

FIGURE CAPTIONS

Fig. 1- Pioneer-10 measurements of the differential cosmic-ray helium spectra at three different heliocentric radial distances. Solid curve is the helium spectrum at the last solar minimum (Gloeckler and Jokipii 1967).

Fig. 2- (a) Differential helium gradient measurements. Solid curves are theoretical calculations of Urch and Gleeson (1972) for various values of the diffusion coefficient κ;
I - κ(1GV) = 7×10^{20}; II - κ(1GV) = 1.4×10^{21};
III - κ(1GV) = 2.8×10^{21} cm^2-sec.

(b) Pioneer 10 different helium gradient between 1.95 and 2.75 AU.

Fig. 3- (a) Time histories of Pioneer-10 and IMP-VI cosmic-ray counting rates. Shaded areas indicate intervals where data was eliminated due to either solar activity or Forbush decreases.

(b) Ratio of Pioneer-10 and IMP-VI counting rates as a function of time and heliocentric radial distance.

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TABLE I

SUMMARY OF PIONEER-10
INTEGRAL GRADIENT MEASUREMENTS

EXPERIMENT	RADIAL DIST. (AU)	ENERGY (MeV)	GRADIENT (%/AU)
U. of Iowa	1.0-3.3	≥80	-0.59 ± 0.60 (DET.C) +0.69 ± 0.61 (DET.D)
U. of Chicago	1.0-2.8	>67	3.0 ± 1.0
Goddard-U.of N.H.	1.0-2.0	>56	2.4 ± 0.3
	2.0-3.2	>56	7.6 ± 0.7

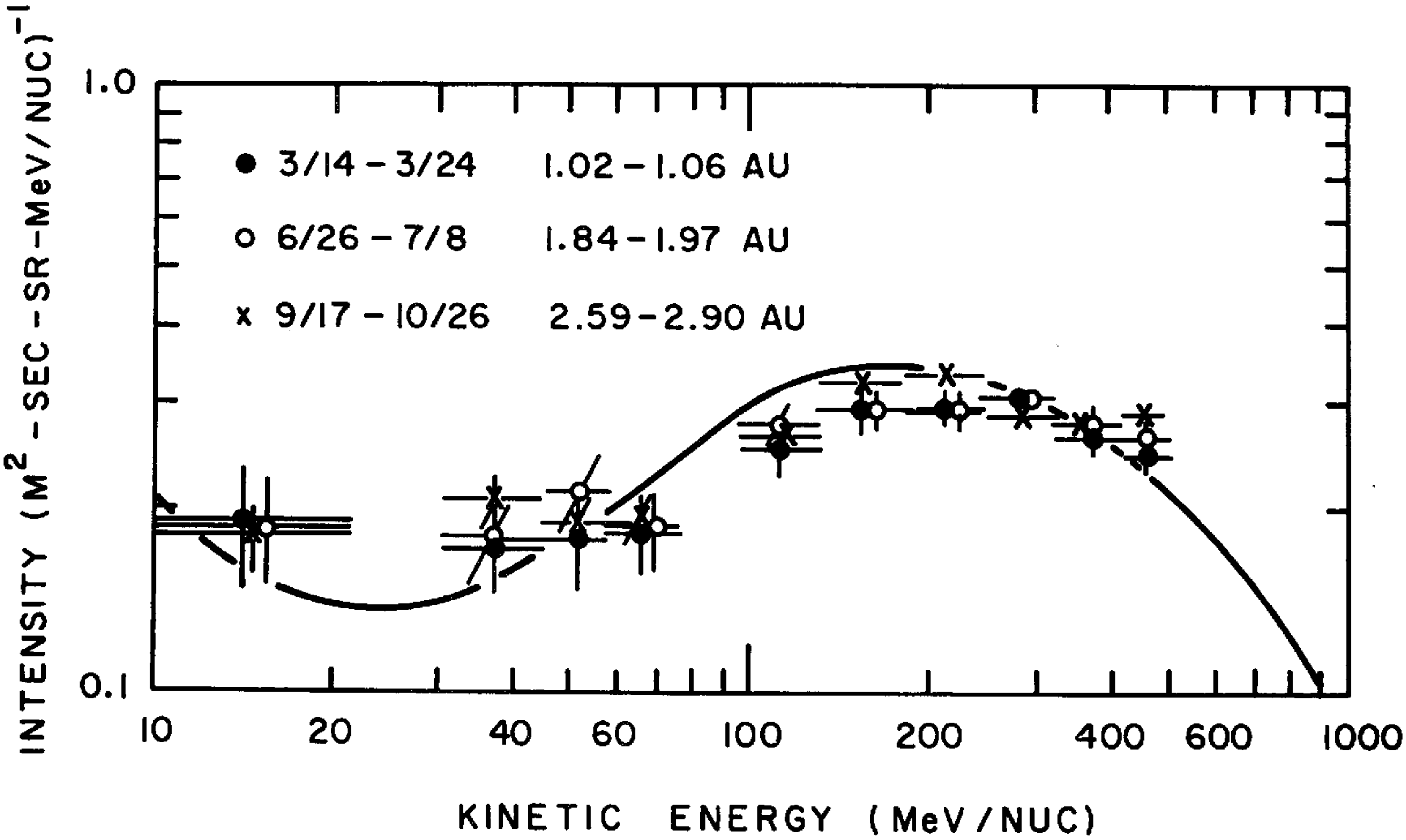
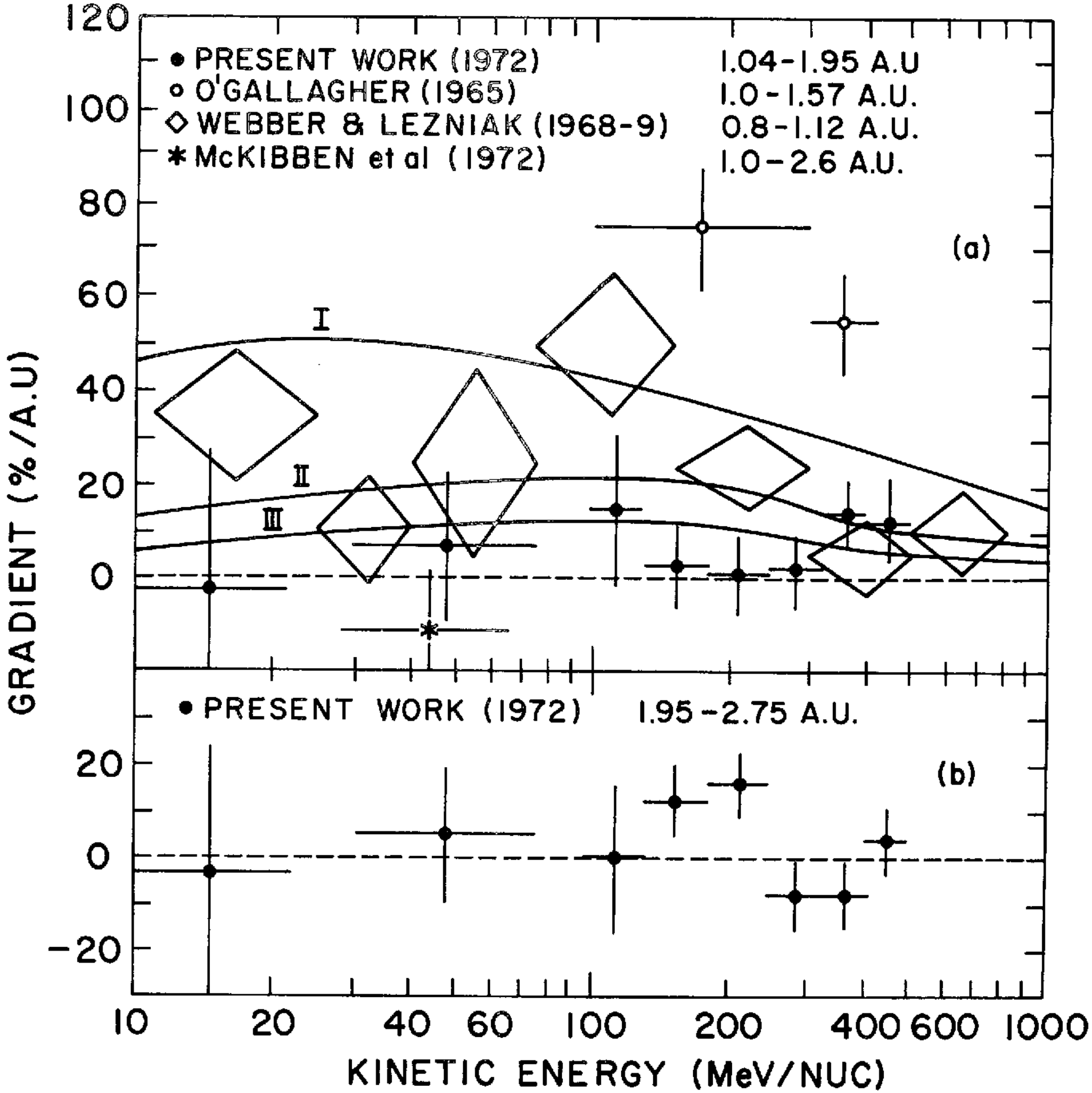

1.0
0.1
INTENSITY $(M^2 - SEC - SR - MeV/NUC)^{-1}$
● 3/14 - 3/24 1.02 - 1.06 AU
○ 6/26 - 7/8 1.84 - 1.97 AU
x 9/17 - 10/26 2.59 - 2.90 AU
10
20
40
60
100
200
400
600
1000
KINETIC ENERGY (MeV/NUC)

Fig. 1



120
100
80
60
40
20
0
-20
GRADIENT (% /A.U)
PRESENT WORK (1972) 1.04-1.95 A.U
O'GALLAGHER (1965) 1.0-1.57 A.U.
WEBBER & LEZNIAK (1968-9) 0.8-1.12 A.U.
McKIBBEN et al (1972) 1.0-2.6 A.U.
(a)
I
II
III
PRESENT WORK (1972) 1.95-2.75 A.U.
(b)
10
20
40
60
100
200
400
600
1000
KINETIC ENERGY (MeV/NUC)

Fig. 2

-13-

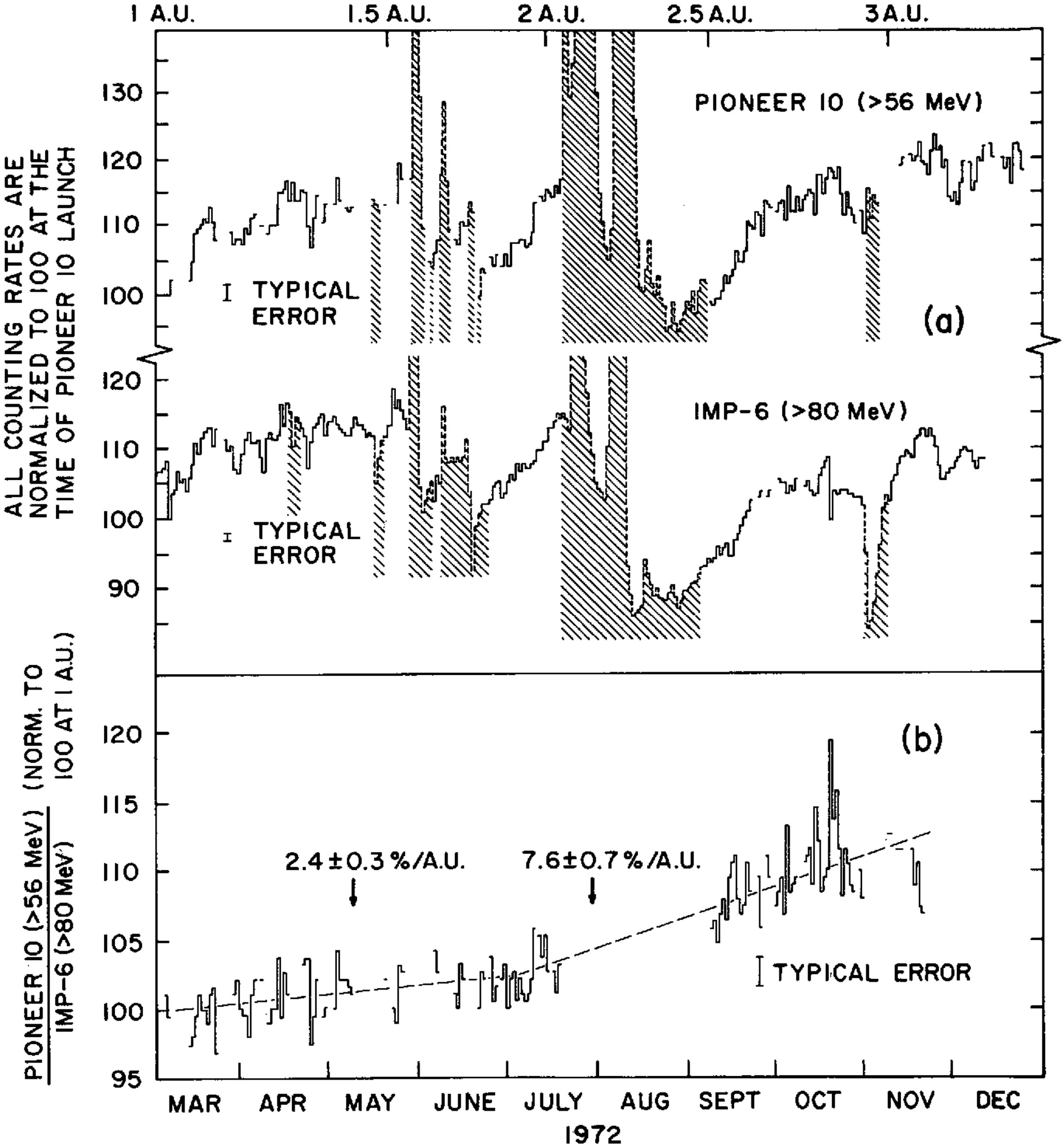

1 A.U.
1.5 A.U.
2 A.U.
2.5 A.U.
3 A.U.
PIONEER 10 (>56 MeV)
TYPICAL ERROR
(a)
IMP-6 (>80 MeV)
TYPICAL ERROR
ALL COUNTING RATES ARE NORMALIZED TO 100 AT THE TIME OF PIONEER 10 LAUNCH
PIONEER 10 (>56 MeV) / IMP-6 (>80 MeV) (NORM. TO 100 AT 1 A.U.)
(b)
2.4±0.3%/A.U.
7.6±0.7%/A.U.
TYPICAL ERROR
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
1972

Fig. 3